Three neutrino flavor oscillations and the atmospheric tau neutrinos

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Abstract

Downward going atmospheric tau neutrino flux is estimated in the presence of three neutrino flavor oscillations for 1 GeV $\leq E \leq 10^3$ GeV. The relative differences between the three and purely two neutrino flavor oscillations are elaborated. As an implication, the downward going atmospheric tau neutrino flux is compared with the galactic plane tau neutrino flux that is also estimated in the presence of three neutrino flavor oscillations. It is pointed out that the galactic plane tau neutrino flux dominates over the downward going atmospheric tau neutrino flux until $E \sim 10$ GeV.

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I. INTRODUCTION

In order to perform a meaningful search of extra-atmospheric neutrinos, the atmospheric neutrino background is needed to be known under various possible approximations [1]. The search for astrophysical tau neutrinos is of special interest since a positive search shall not only yield the useful information from the surrounding cosmos but shall also corroborate the neutrino flavor mixing hypothesis [2].

In view of the presently available restricted ranges of the various neutrino mixing parameters in the three neutrino flavor approximation [3], as well as the recent relevant detector developments [4], it is of some interest to estimate the resulting new atmospheric tau flux. Such studies may also provide some examples of `new windows` to study the cosmos around us, that shall open up under the hypothesis of the neutrino oscillations.

Previously, there is `no` attempt to estimate the atmospheric tau neutrino flux in the context of three neutrino flavor oscillations framework. So far, the atmospheric tau neutrino flux is estimated in two neutrino flavor approximation only [5]. Recently, it is pointed out that the tau neutrino astronomy in the multi-GeV energy range is possible, at least in principle. It is so, because the atmospheric ν_τ flux is generally suppressed compared to the atmospheric ν_μ flux, as a result the prospective observation of astronomical ν_τ suffers `much less` background than in the ν_μ case. The zenith angle (ξ) dependence of the atmospheric background tau neutrino flux is also crucial in determining the possible future prospects [6]. This is an example of the availability of a new cosmic horizon because of the neutrino oscillations, and is true for `tau neutrinos only` among the three neutrino flavors.

It is also pointed out that for $0^\circ \leq \xi \leq 60^\circ$, the downward going atmospheric tau neutrino flux is minimum, thus providing an opportunity to search for extra-atmospheric tau neutrinos in this zenith angle range, in the presence of neutrino oscillations [7]. The neutrino oscillation effects are minimal for the down ward going atmospheric neutrinos. As a result, the oscillated atmospheric tau neutrino flux provides a minimal background for prospective astronomical tau neutrino flux searches.

Collectively, in these papers it is pointed out that `contrary` to general expectations, the atmospheric neutrino flux does not smear out the astronomical neutrino flux on the Earth at low energy ($E < 10^3$ GeV) once the flavor composition of the incoming neutrino flux is taken into account.

In this paper, we estimate the atmospheric tau neutrino flux in three neutrino flavor mixing approximation. This is an extension of the above mentioned previous works in this direction. As an implication of this estimate, we compare it with galactic-plane tau neutrino flux in the presence of neutrino oscillations. It is pointed out that the `dominance` of galactic plane tau neutrino flux over the downward atmospheric tau neutrino flux still persists in the multi-GeV energy range.

The considered energy range (1 GeV $\leq E \leq 10^3$ GeV) is interestingly within the reach of presently operating detectors as well as those under active planning [4]. Tau neutrino flavor discrimination is an interesting challenge for the existing/forthcoming astrophysical neutrino telescopes.

This paper is organized as follows. In section II, the electron, muon and tau neutrino flux originating from the Earth atmosphere is briefly discussed. In section III, the neutrino oscillation effects are studied for these. In section IV, an implication of our estimate for the atmospheric tau neutrinos is mentioned, whereas in section V, conclusions are presented.

II. ATMOSPHERIC NEUTRINO FLUX

Atmospheric neutrino flux arises when the incoming cosmic rays interact with the air nuclei A, in the Earth atmosphere [8]. For 1 GeV $\leq E \leq 10^3$ GeV, the π, the K productions and their direct and indirect decays are the main sources of electron and muon neutrinos, both being in the region of conventional neutrino production. The absolute normalization of the conventional atmospheric neutrino flux is presently known to be no better than $(20-25)\%$ in the above energy range [9]. For present estimates, the non tau atmospheric neutrino flux is taken from Ref. [10]. These are atmospheric neutrino flux calculations in one dimension without geomagnetic field effects. At higher energy, the prompt muon neutrino production from D's dominates over the conventional one [11].

The atmospheric tau neutrino flux arises mainly from production and the decay of D_S and is calculated in Ref. [12, 13]. The Quark Gluon String Model (QGSM) is used in Ref. [13] to model the pA interactions. The low energy atmospheric tau neutrino flux is essentially isotropic [12]. For $E \leq 10^2$ GeV, the atmospheric tau neutrino flux is obtained by following the procedure given in Ref. [12, 13] and re-scaling w.r.t new cosmic ray flux spectrum, taking it to be predominantly the protons [14].

For illustrative purpose, the three downward going ($\cos\xi = 1$) atmospheric neutrino fluxes $F^0_\nu(E) \equiv \mathrm{d}^2N^0_\nu/\mathrm{d}(\log_{10}E)\mathrm{d}\xi$, in units of $\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$, estimated using the above description, are shown in Fig. 1 as a function of the neutrino energy.

III. NEUTRINO OSCILLATION ANALYSIS: THE ATMOSPHERIC TAU NEUTRINO FLUX

We shall perform here the three neutrino flavor oscillation analysis. In the context of mixing in three flavors, the neutrino mixing parameters are : δm^2_{12}, δm^2_{23}, δm^2_{13}, θ_{12}, θ_{23}, θ_{13} and the CP violating phase δ. The $\delta m^2_{ij} \equiv |m^2_i - m^2_j|$, where $i, j = 1, 2, 3$, is the absolute difference of the mass squared value of the mass eigenstates and the three θ_{ij}'s are the mixing angles.

Presently, the δm^2_{12} and θ_{12} are mainly determined from the data analysis of the solar neutrino flux measurements [15]. The neutrino mixing parameters inferred from solar neutrino flux studies are recently confirmed by a terrestrial reactor experiment, namely Kamiokande Liquid-scintillation Anti-Neutrino Detector (KamLAND) [16]. The δm^2_{23} and θ_{23} are mainly determined from the study of the atmospheric neutrinos [17]. The above neutrino mixing parameters inferred from atmospheric neutrino flux studies are also recently confirmed by a terrestrial accelerator experiment, namely KEK to Kamiokande long-baseline neutrino experiment (K2K) [18]. The θ_{13} is mainly constrained by the CHOOZ experiment [19]. For some recent feasibility studies to determine more precisely the θ_{13} and/or δ, see [20]. The total range of δm^2 irrespective of neutrino flavor in the context of three neutrino flavors is $10^{-5}\ \mathrm{eV}^2 \leq \delta m^2 \leq 10^{-3}\ \mathrm{eV}^2$.

Under the assumption that $\delta = 0$, the 3×3 Maki Nakagawa Sakata (MNS) mixing matrix U in standard parameterization connecting the neutrino mass and flavor eigenstates reads [21]:

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13} & c_{12}c_{23} - s_{12}s_{23}s_{13} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13} & -c_{12}s_{23} - s_{12}c_{23}s_{13} & c_{23}c_{13} \end{pmatrix}, \tag{1}$$

where $c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} \equiv \sin\theta_{ij}$. The presently available empirical constraints for the

various neutrino mixing parameters give the elements of the above U matrix as

$$U \equiv \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 0.84 & 0.54 & 0.10 \\ -0.44 & 0.56 & 0.71 \\ 0.32 & -0.63 & 0.71 \end{pmatrix}. \tag{2}$$

A recent short summary of the model predictions for the expected magnitude of $|U_{e3}|$ is given in Ref. [22]. Using Eq. (1), the neutrino flavor oscillation probability formula is [23]

$$P(\nu_\alpha \to \nu_\beta; E, \xi) \equiv P_{\alpha\beta} = \sum_{i=1}^{3} U_{\alpha i}^2 U_{\beta i}^2 + \sum_{i \neq j} U_{\alpha i} U_{\beta i} U_{\alpha j} U_{\beta j} \cos\left(\frac{2L}{L_{ij}}\right), \tag{3}$$

where $\alpha, \beta = e, \mu, \tau$ and $L_{ij} \simeq 4E/\delta m_{ij}^2$ is the neutrino oscillation length. The L in Eq. (3) is the neutrino flight length. In the Earth atmosphere, it can be estimated using the relation

$$L = \sqrt{(h^2 + 2R_\oplus h) + (R_\oplus \cos\xi)^2} - R_\oplus \cos\xi, \tag{4}$$

where ξ is the zenith angle. The L is essentially the distance between the detector and the height at which the atmospheric neutrinos are produced. The $R_\oplus \simeq 6.4 \cdot 10^3$ km is the Earth radius, and for instance, $h_\mu = 15$ km is the mean altitude at which the atmospheric muon neutrinos are produced. In general, h is not only a function of the zenith angle ξ, the neutrino flavor but also the neutrino energy [24].

We consider the zenith angle range between 0° and 60°. Because in this energy range i) as pointed out in Ref. [7], the atmospheric neutrino oscillation effect is minimal, ii) the Earth curvature effects can be ignored, and iii) more relevant for present discussion is that in this zenith angle range, the matter effects in neutrino oscillations are negligible as the Earth atmosphere matter density traversed by neutrino satisfies: $\rho < \rho_{\rm res}$ where $\rho_{\rm res} \equiv m_N \Delta \cos 2\theta/\sqrt{2} G_F$, with $\Delta \equiv \delta m^2/2E$ ranges between 10^{-17} eV and 10^{-12} eV, for the entire considered δm^2 and E ranges. Fig. 2 shows an example of $P_{\mu\tau}$ using Eq. (3) for four different ξ values where $\xi = 0^\circ$ corresponds to the downward going atmospheric neutrinos. A relevant remark useful for what follows next is that for $E < 20$ GeV, the $P_{\mu\tau}$ is larger by a factor of up to ~ 8 for larger ξ, owing to the fact that for larger ξ, neutrinos traverse larger distance in Earth atmosphere.

In the limit $\theta_{12}, \theta_{13} \to 0$, we obtain the commonly used two neutrino flavor oscillation probability formula for $P(\nu_\mu \to \nu_\tau; E, \xi)$ as

$$P_{\mu\tau} = \sin^2 2\theta_{23} \cdot \sin^2\left(1.27 \frac{\delta m_{23}^2(\mathrm{eV}^2) L(\mathrm{km})}{E(\mathrm{GeV})}\right), \tag{5}$$

where $\sin 2\theta_{23} = 2c_{23}s_{23}$. The neutrino flux $F_{\nu_\alpha}(E,\xi)$, arriving at the detector, in the presence of neutrino oscillations is estimated using

$$F_{\nu_\alpha}(E,\xi) = \sum_\beta P_{\alpha\beta}(E,\xi) F^0_{\nu_\beta}(E,\xi), \tag{6}$$

where $F^0_{\nu_\beta}(E,\xi)$ are taken according to discussion in section II. The $P_{\alpha\beta}(E,\xi)$ is a 3×3 matrix obtainable using Eq. (3). The unitarity conditions such as $1 - P_{ee}(E,\xi) = P_{e\mu}(E,\xi) + P_{e\tau}(E,\xi)$ are implemented at each E and ξ at which these are evaluated. Fig. 3 shows comparison of the atmospheric tau neutrino flux for $\xi = 0^{\circ}$ and $\xi = 60^{\circ}$ in three and two neutrino flavor mixings as a function of the neutrino energy. Note the difference in the slope in three and two neutrino flavor approximations because of the presence of second δm^2 scale in three flavor mixing relative to only one δm^2 scale in purely two neutrino flavor approximation. The atmospheric tau neutrino flux for larger zenith angles is larger relative to smaller zenith angles for $E < 20$ GeV (see Fig. 2 also).

The downward going atmospheric tau neutrino flux in the presence of three neutrino flavor oscillations can be parameterized for 1 GeV $\leq E \leq 10^2$ GeV as

$$F_{\nu_\tau}(E) = A - Bx^{-1} + Cx^{-2} + Dx^{-3} - Ex^{-4}, \tag{7}$$

where the coefficients are $A = 4.20865 \cdot 10^{-11}$, $B = 1.57226 \cdot 10^{-8}$, $C = 5.37912 \cdot 10^{-6}$, $D = 3.97309 \cdot 10^{-5}$ and $E = 2.21708 \cdot 10^{-5}$ with $x = E/\text{GeV}$. The $F_{\nu_\tau}(E)$ is in units of $\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$.

IV. AN IMPLICATION: COMPARISON WITH THE GALACTIC PLANE TAU NEUTRINO FLUX

In this section, we shall estimate the galactic plane tau neutrino flux with three neutrino flavor mixing. This is to *illustrate* a `new` opportunity we may have to study cosmos having estimated the related atmospheric tau neutrino background.

The galactic plane electron and muon neutrino flux is calculated in Ref. [25], whereas the galactic plane tau neutrino flux is calculated in Ref. [13]. These calculations consider pp interactions inside the galaxy with target proton number density $\sim 1/\text{cm}^3$ along the galactic plane, under the assumption that the cosmic ray flux spectrum in the galaxy is constant at

its locally observed value. We emphasize that because of above uncertainties, the galactic plane neutrino fluxes should only be considered as reference upper limits.

Following Ref. [13], the galactic plane neutrino flux for 1 GeV $\leq E \leq 10^3$ GeV is obtained by re-scaling w.r.t new cosmic ray flux spectrum. The tau neutrino production is rather suppressed in the galactic plane relative to muon neutrino production. In general, the non tau neutrino flux is larger than the tau neutrino flux for $E \leq 10^3$ GeV from the above two sites.

In order to estimate the oscillation effect, the distance L for galactic plane neutrinos can be taken as $\sim$ 5 kpc, where 1 pc $\sim 3 \times 10^{13}$ km. This imply that $L_{ij} \ll L$, namely the galactic plane neutrino flux oscillate before reaching the earth. Thus, the galactic plane neutrino flux is averaged out for the whole range of δm^2 in the entire considered energy range. Under the assumption of averaging over rapid oscillations, we obtain from Eq. (3)

$$P_{\alpha\beta} \simeq \sum_{i=1}^{3} U_{\alpha i}^2 U_{\beta i}^2. \tag{8}$$

The 3×3 P matrix using Eq. (2) in above Eq. is

$$P \equiv \begin{pmatrix} P_{ee} & P_{e\mu} & P_{e\tau} \\ P_{e\mu} & P_{\mu\mu} & P_{\mu\tau} \\ P_{e\tau} & P_{\mu\tau} & P_{\tau\tau} \end{pmatrix} = \begin{pmatrix} 0.59 & 0.23 & 0.20 \\ 0.23 & 0.39 & 0.39 \\ 0.20 & 0.39 & 0.42 \end{pmatrix}. \tag{9}$$

Note that this P matrix is independent of not only δm^2 but also E (and ξ). A rather similar 3×3 P matrix was obtained for both vanishing δ and θ_{13} in Ref. [26].

Using Eq. (6) and Eq. (9), the galactic plane tau neutrino flux is estimated in the presence of three neutrino mixing. It is then compared with the atmospheric tau neutrino flux in Fig. 4. The comparison includes the two neutrino flavor approximation effect with maximal 23 mixing also. From the figure, it can be seen that the galactic plane/non-atmospheric tau neutrino flux starts `dominating` over the downward going atmospheric tau neutrino flux even for E as low as 10 GeV in the presence of neutrino oscillations, depending upon the incident zenith angle for Atmospheric neutrinos (the galactic plane neutrino flux is independent of the zenith angle). This is a very specific feature of `tau neutrinos`, and is absent for electron and muon neutrinos. This specific behavior has to do with the `neutrino oscillations`. The galactic plane tau neutrino flux in three neutrino mixing is smaller by a factor $\sim 2/3$ relative to two neutrino flavor mixing, irrespective of the neutrino energy.

Fig. 4 indicates that zenith angle dependence of the total tau neutrino flux can at least in principle help to distinguish between atmospheric and non-atmospheric tau neutrino flux. The galactic plane tau neutrino flux dominance is `independent` of number of oscillating neutrino flavors (two or three). The galactic tau neutrino flux transverse to the galactic plane is three to four orders of magnitude smaller than the galactic plane one [13].

Fig. 5 shows the three downward going atmospheric neutrino fluxes in the presence of three neutrino flavor mixing, along with the corresponding galactic plane neutrino fluxes. Here the contribution from the charm production is also taken into account [27]. The galactic plane three neutrino flavor fluxes are approximately equal because of Eq. (9). The unique behavior of atmospheric oscillated tau neutrino flux relative to electron and muon neutrino flux is evident. The `oscillated` galactic plane tau neutrino flux thus `dominates` until approximately 10 GeV over the corresponding atmospheric neutrino background. On the other hand, the same occurs at E $\sim 10^5$ GeV and E $\sim 10^6$ GeV for electron and muon neutrino fluxes in the presence of three neutrino flavor mixing from the two astrophysical sources under discussion. The change in the slope of the atmospheric electron and muon neutrino fluxes is a reflection of the corresponding change in the slope of cosmic-ray flux.

In general, the three downward atmospheric neutrino fluxes provide an `energy dependent` background to the incoming astronomical neutrino flux in the `presence` of neutrino oscillations. This observation may have some relevance for the forthcoming neutrino telescopes with the prospective neutrino flavor discrimination capabilities.

The galactic plane tau neutrino flux for 1 GeV $\leq E \leq 10^3$ GeV in the presence of three neutrino flavor mixing can be parameterized as

$$F_{\nu_\tau}(E) = 4.38 \cdot 10^{-6} \cdot E^{1.07} \left[E + 2.15 \exp(-0.21\sqrt{E})\right]^{-2.74}, \tag{10}$$

where $F_{\nu_\tau}(E)$ is in units of cm^{-2}s^{-1}sr^{-1} and on r.h.s. E is in units of GeV.

We have estimated the galactic plane tau neutrino induced shower event rate for the forthcoming Mega ton (Mt) class of detectors [28], to indicate the limited prospects offered by below TeV (1 TeV = 10^3 GeV) tau neutrino astronomy to search for extra-atmospheric astrophysical neutrino sources in this energy range, as envisaged presently. The tau neutrino event rate $N_{\rm event}$ for 10 GeV $\leq E \leq 10^3$ GeV can be approximately estimated as

$$N_{\rm event} = \int_{E^{\rm min}}^{E^{\rm max}} F_{\nu_\tau}(E) \cdot \sigma_{\nu_\tau \to {\rm shower}}(E) \frac{{\rm d}E}{E}. \tag{11}$$

The $F_{\nu_\tau}(E)$ is the galactic plane tau neutrino flux in the presence of neutrino oscillations in units of $\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ and is given by Eq. (10). The $\sigma_{\nu_\tau \to \mathrm{shower}}(E)$ is $\sigma^{\mathrm{CC}}_{\nu_\tau N}(E)/\mathrm{Mt}$, where one megaton of water contains $\sim 5.5 \cdot 10^{35}$ nucleons [29]. The $\sigma_{\nu_\tau \to \mathrm{shower}}(E)$ is taken from the web site of Cern Neutrinos to Gran Sasso (CNGS) experiment [30]. The N_{event} is found to be in the range 1 to 10 in units of $\mathrm{Mt}^{-1}\mathrm{yr}^{-1}$ over $2\pi \cdot \mathrm{sr}$ with a 3 to 5 years of data taking.

V. CONCLUSIONS

Atmospheric tau neutrino flux is estimated for 1 GeV $\leq E \leq 10^3$ GeV in the presence of neutrino oscillations. The three neutrino flavor oscillation study is carried out. The relative difference between two and three neutrino flavor oscillation analysis is elaborated.

As an implication of this study, the atmospheric tau neutrino flux is compared with the galactic plane tau neutrino flux with three neutrino mixing. It is pointed out that the dominance of galactic plane tau neutrino flux persists over the downward going ($\xi = 0^\circ$) atmospheric tau neutrino flux for $E \geq 10$ GeV relative to $E \geq 8$ GeV in two flavor approximation. The same dominance shifts to $E \geq 10$ GeV relative to $E \geq 9$ GeV for $\xi = 60^\circ$.

In the multi-GeV energy range, the dominance of the galactic plane tau neutrino flux over the atmospheric tau neutrino flux for incident zenith angle between 0° and 60° in the presence of neutrino oscillation both in two and three neutrino mixing is `unique` to tau neutrinos only. The galactic electron and muon neutrino flux dominance starts only for $E \geq 10^5$ GeV irrespective of mixed (two or three) neutrino flavors.

Summarizing, a possibility of a `neutrino flavor dependent new window` in low energy neutrino astronomy seems to exist. Our present study is an attempt to justify this existence. Namely, for the incident neutrino energy range between 10s of GeV up to 1000s of GeV, in which the presently data taking large neutrino detectors such as the Antarctic Muon And Neutrino Detector Array (AMANDA) experiment [31] at the south pole and the Baikal experiment [32] in the lake Baikal in Russia are not (yet) optimized to perform extra-atmospheric neutrino astronomy, the upcoming Mega ton class of detectors (or even the currently existing ones) should at least in principle be able to do possibly a meaningful neutrino astronomy based on prospective neutrino flavor identification.

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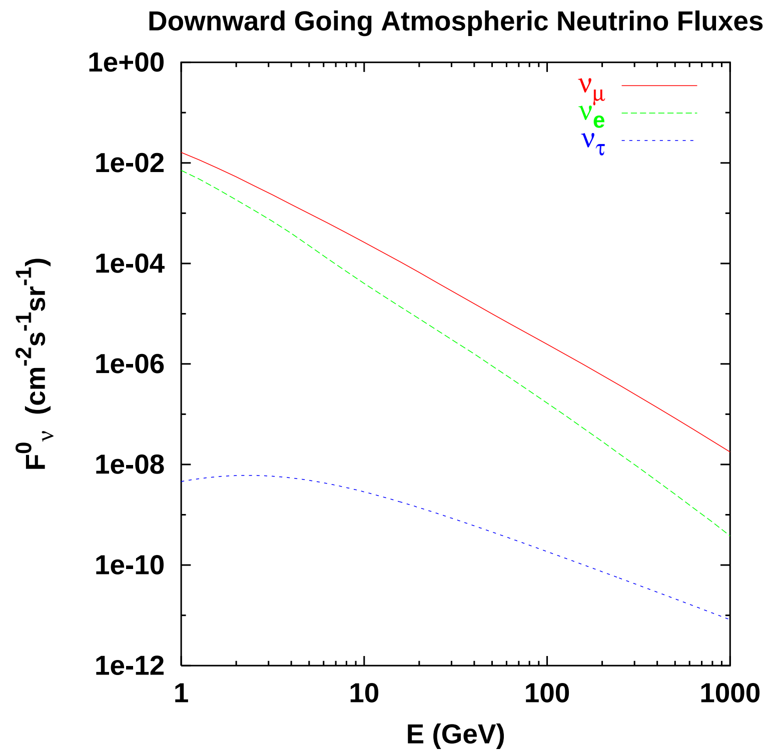

FIG. 1: The down ward going atmospheric electron, muon and tau neutrino fluxes as a function of the neutrino energy. *Absence* of neutrino oscillations is assumed here. More details are given in the text.

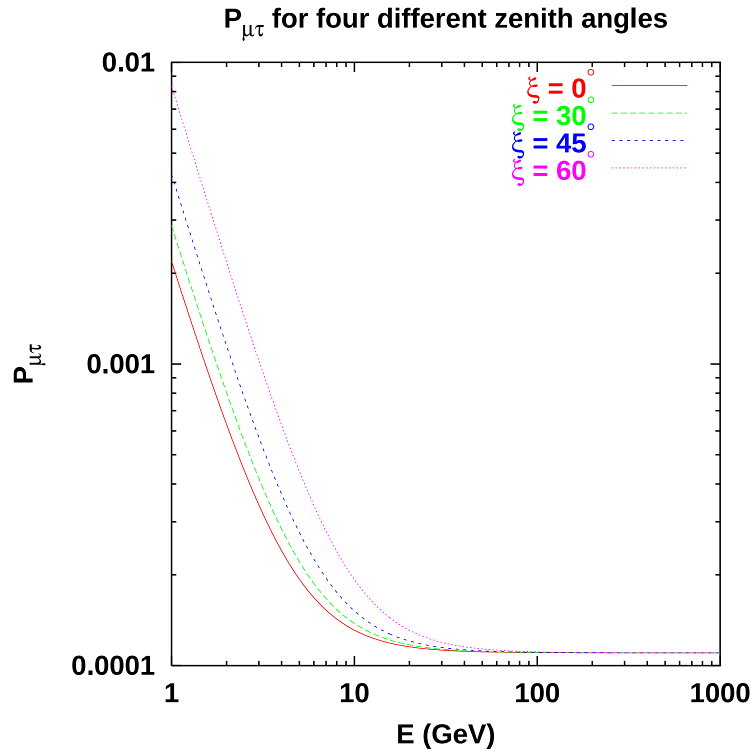

FIG. 2: An illustration of $P_{\mu\tau}$ for four different ξ values, as a function of the neutrino energy. Three neutrino flavor mixing is assumed here.

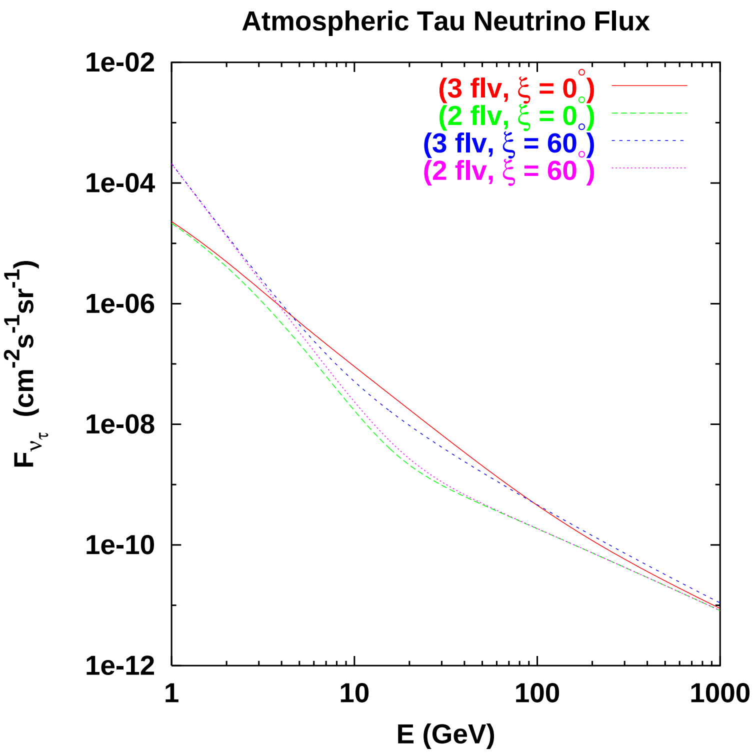

FIG. 3: The downward going atmospheric tau neutrino flux in the three and the two neutrino mixings for $\xi = 0^{\text{o}}$ and $\xi = 60^{\text{o}}$ as a function of the neutrino energy.

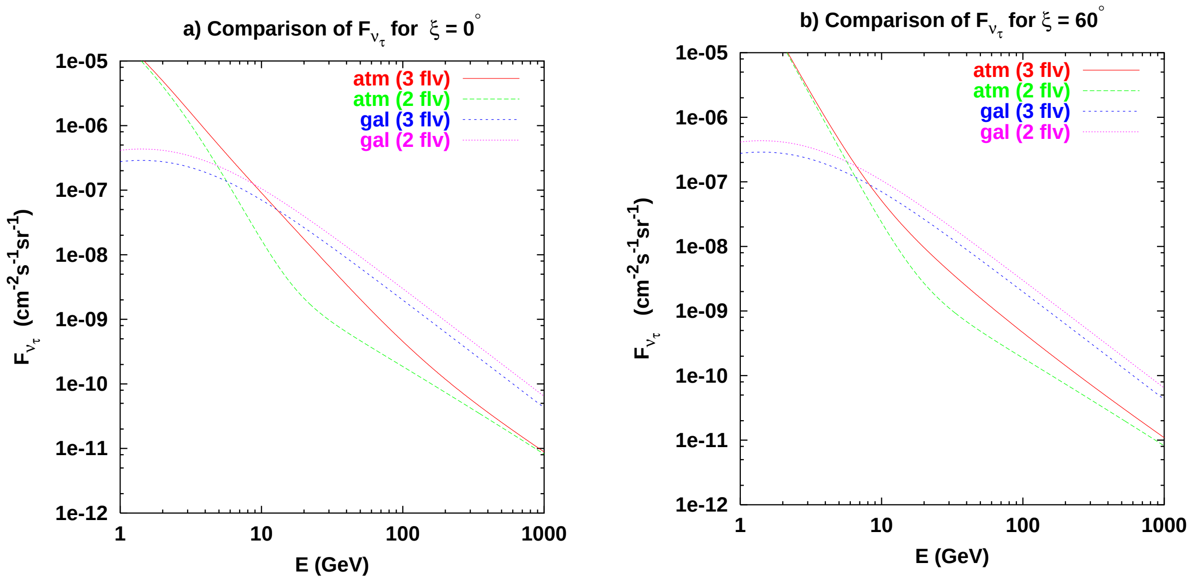

FIG. 4: Left panel: The comparison of the galactic plane and the downward going atmospheric tau neutrino flux for $\xi = 0^{o}$ as a function of the neutrino energy. Three flavor neutrino mixing is assumed. Also shown is two neutrino flavor mixing results with maximal 23 mixing. Right panel: Same as left panel but for $\xi = 60^{o}$.

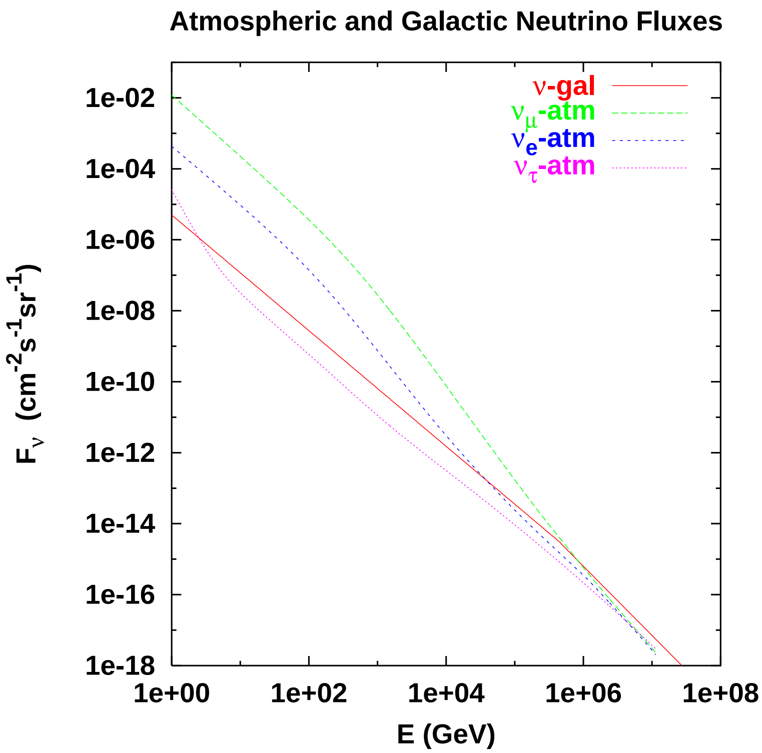

FIG. 5: The down ward going atmospheric electron, muon and tau neutrino fluxes as a function of the neutrino energy in the presence of three neutrino flavor mixing. The galactic plane neutrino flux estimated in three neutrino neutrino flavor mixing is also shown for comparison.